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Characterization of Fuel Cell Duty Cycle Elements

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Characterization of Fuel Cell Vehicle Duty Cycle Elements

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Abstract

This report covers research done as part of US Department of Energy contract DE-PS26-99FT14299 with the Fuel Cell Propulsion Institute on the fuel cell RATLER™ vehicle, Lurch, as well as work done on the fuel cells designed for the vehicle. All work contained within this report was conducted at the Robotic Vehicle Range at Sandia National Laboratories in Albuquerque New Mexico. The research conducted includes characterization of the duty cycle of the robotic vehicle. This covers characterization of its various abilities such as hill climbing and descending, spin-turns, and driving on level ground. This was accomplished with the use of current sensors placed in the vehicle in conjunction with a Data Acquisition System (DAS), which was also created at Sandia Labs. Characterization of the two fuel cells was accomplished using various measuring instruments and techniques that will be discussed later in the report. A Statement of Work for this effort is included in Appendix A. This effort was able to complete characterization of vehicle duty cycle elements using battery power, but problems with the fuel cell control systems prevented completion of the characterization of the fuel cell operation on the benchtop and in the vehicle. Some data was obtained characterizing the fuel cell current-voltage performance and thermal rise rate by bypassing elements of the control system.

Experimental Setup

Data Acquisition System

The data acquisition system (DAS) was built around a Tern A-Engine86 single-board computer running at 40MHz and able to store 256K-word (dual-byte) data values. A custom board was built to provide gain and offset signal conditioning of voltage signals to the onboard A-to-D converters. These boards were combined with a battery power supply and voltage regulators and mounted in a custom box which could be mounted on a vehicle to operate as a stand-alone data acquisition system. (Fig. 1.)

Three Amploc PRO 5 current sensors were used to take measurements on the fuel cell powered vehicle. These sensors have a positive current threshold of about 8.5 amps, which was good enough to detect high momentary current spikes. One sensor was placed at each of the motor amps in each body half. The third sensor was placed directly on the output of the 24V series battery connection. These three sensors were connected directly to the DAS, which was mounted on top of the vehicle body. They were calibrated by running known currents through a calibration wire threaded through the sense hole of each sensor. The DAS takes about 90 seconds of data at a rate of about 1 data point every 3 milliseconds.

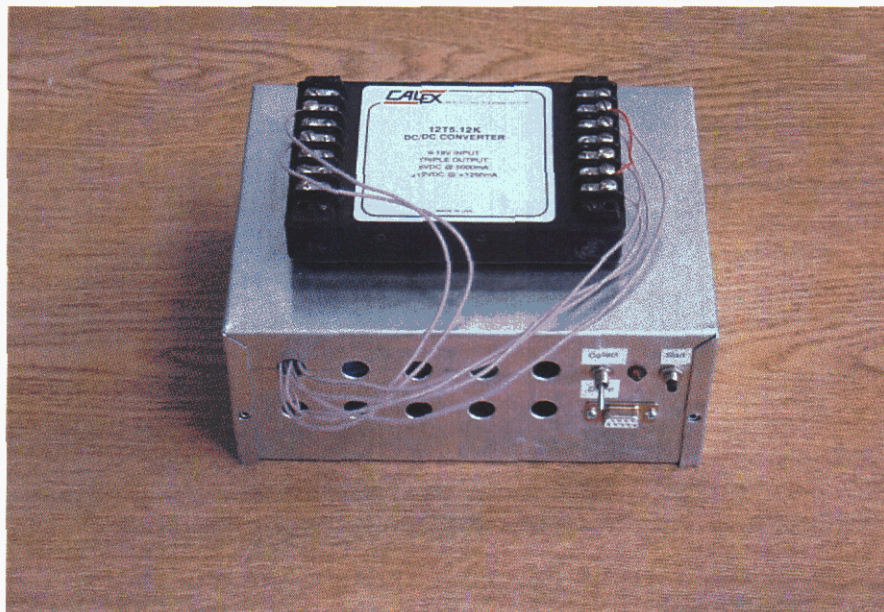


Figure 1. Data Acquisition System

Fuel Cells

The fuel cells were tested and analyzed only on the benchtop using various measuring instruments including: a clamp-on current probe, an infrared temperature sensor, voltmeters, a stopwatch, and a digital scale. The digital scale was used to measure the difference in weight of each fuel cell before and after filling, so as to measure the rate at which hydrogen was used up. A bank of resistors was used to load the fuel cells in increments and provide a source of current draw. A voltmeter was used to measure output

voltage at each level of resistance and a clamp-on current meter was used to measure current draw at each resistance.

Testing Procedures

Duty Cycle Characterization

The highest priority activity was to characterize the duty cycle of the vehicle, that is its cyclic sequence of expected motions. Because there is no one specific activity that will be required of the vehicle, this characterization was approached by breaking down vehicle activities into sub elements and characterizing the power and energy requirements for each motion activity element. These can then be strung together in various combinations to characterize an array of various potential activities and missions. The vehicle was operable with batteries, but the path to get the vehicle operating with the fuel cells would require significant testing and was not guaranteed to be successful, so we began the program by characterizing the vehicle duty cycle elements using batteries to power the vehicle. Testing of the vehicle consisted of running the vehicle under different conditions with the DAS mounted on top to enable data capture of each specific run. (Figs. 2 and 3.) Data was taken on several different runs, which included terrain such as flat asphalt, flat gravel, dirt hills, curved motocross track sections, and turns. A significant effort was required at the beginning of the program to develop the DAS and get it operational on the vehicle.

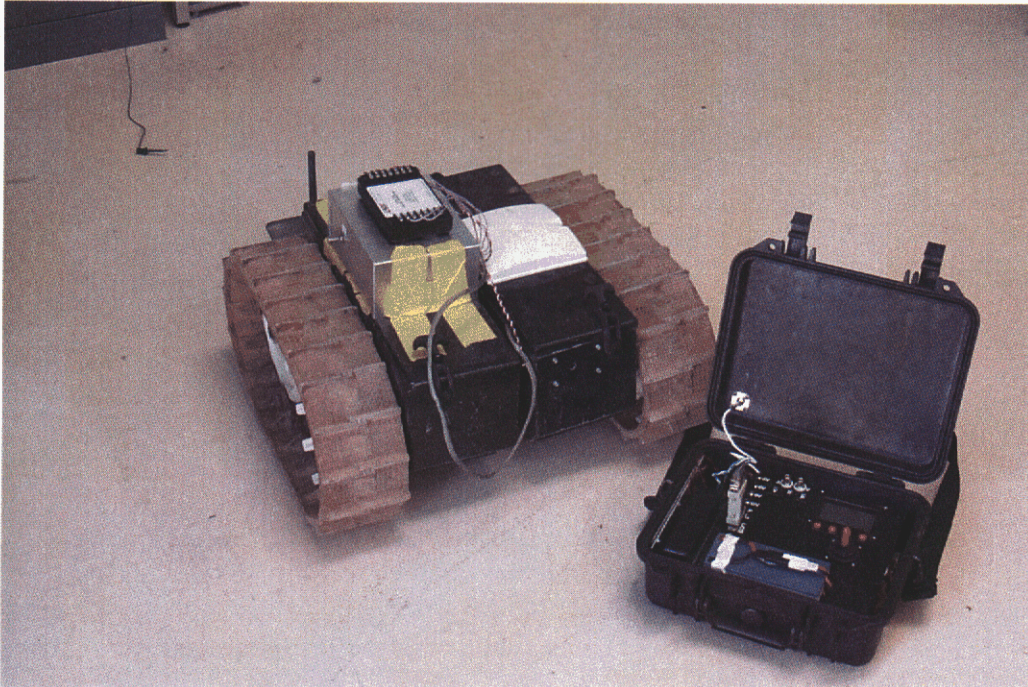


Figure 2. View of Vehicle with DAS and Operator Control Unit



Figure 3. View of Vehicle During Test

Fuel Cell Characterization

A cautious approach was taken to getting the fuel cell operating in the vehicle in order to avoid any possibility of overheating and damaging the fuel cells, a problem which has occurred in prior testing. In prior tests the cells were connected in parallel. To avoid the possibility that one fuel cell could absorb the full vehicle load and overheat while the other fuel cell contributed less, we rewired the vehicle so that each fuel cell operated independently rather than in parallel. Another concern was that there was inadequate cooling of the stack in the vehicle either due to inadequate outside airflow or due to inadequate ducting of the air across the stack. While there is an over-temperature shutdown feature using a thermocouple mounted on the stack, it is not clear why this did not prevent damage to the stack in prior tests. The placement of the thermocouple could have been at fault, the stack could have overheated rapidly at the core before the thermocouple had time to react, or the control system could have failed to shut down the system in time. In light of these concerns, a progressive approach was planned to get the fuel cells operable on the benchtop and to gradually introduce conditions simulating operation in a vehicle before placing the stack in the vehicle for testing.

Benchtop testing was approached by testing in free air with a large cooling fan and monitoring stack temperature manually. Initial tests were aimed at checking out the fuel cell and controller performance. The fuel cell was characterized by obtaining a current-voltage (IV) plot over a range of loads and by measuring the rate of temperature rise as a function of load. We began by first weighing each cell prior to filling, then filling the hydride bed for about an hour and a half with hydrogen. Filling the beds of each fuel cell was accomplished through the use of the filling manifold built by Paul Baca (Dept.6245 Catalysis and Chemical Technologies). Once filled, each fuel cell was connected to the resistor bank and the cell was turned on. Measurements were then made approximately every minute for stack temperature, voltage and current output, and elapsed time.

Data and Results

Duty Cycle Characterization on Batteries

The first set of data, shown in Figs. 4a., 4b., and 4c., gives the results from a run of the robot on level asphalt. The vehicle was driven forward for some time, then a spin-turn was done and then it was driven in reverse with some slight turning done in both directions. The data is presented as recorded, at $\sim 3\text{msec}$ intervals, then as 0.1 and 1 second running averages. The instantaneous data is fast enough to capture the pulse-width modulation of the motor controllers that cycles between full and zero current at a high frequency. The averaged data reduces the spikiness of the data to reveal the average power expended at the expense of the actual dynamic variation. Notice the data is clipped by the current sensors at about 8.5 to 9A. A short startup spike can be seen at the beginning of motion with a magnitude of 8 to 9A for each motor but with little actual energy. We would expect that with a power system unable to provide this current draw the startup inrush would be less but longer resulting in little apparent difference in performance. Figure 5. shows a close up of the spin-turn during the interval between seconds 24 and 25.

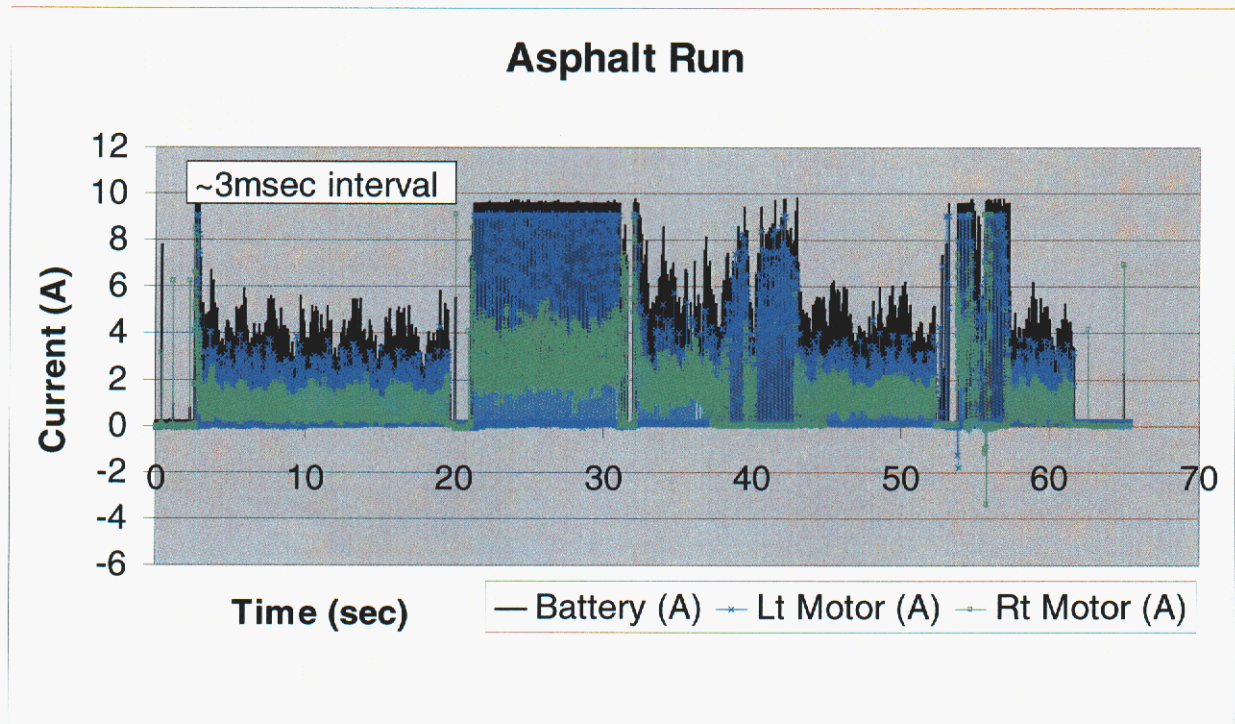


Figure 4a. Asphalt Surface: Forward, Spin-Turn, Reverse ($\sim 3\text{msec}$ interval readings)

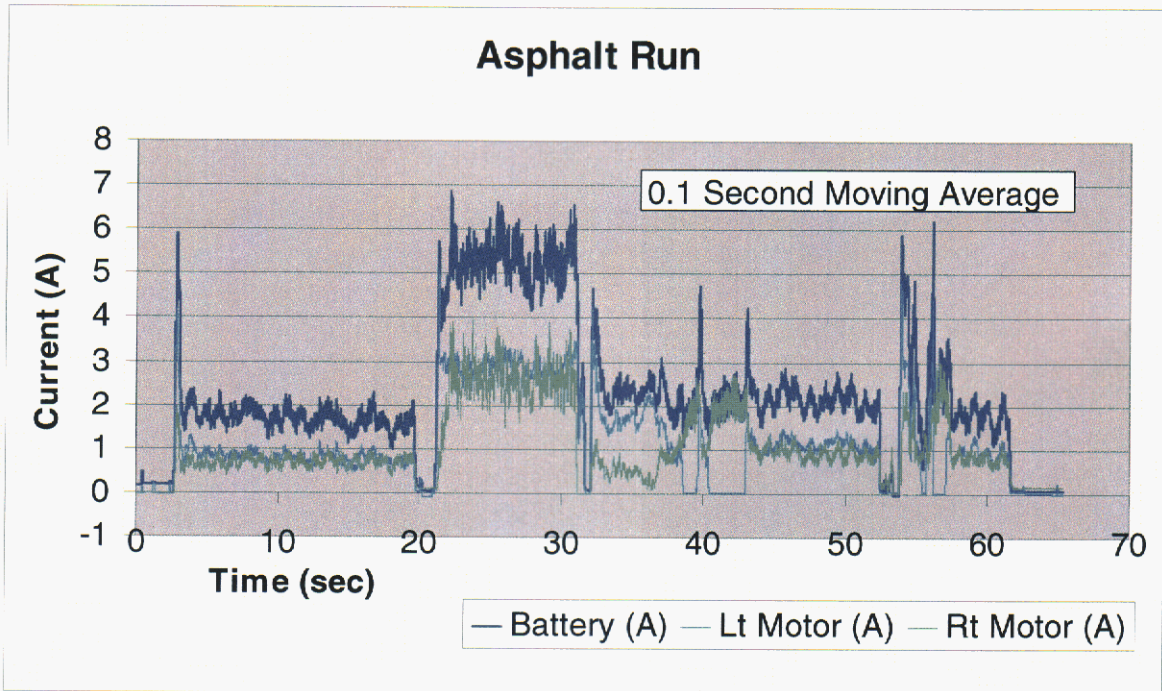


Figure 4b. Asphalt Surface: Forward, Spin-Turn, Reverse (0.1 sec moving avg.)

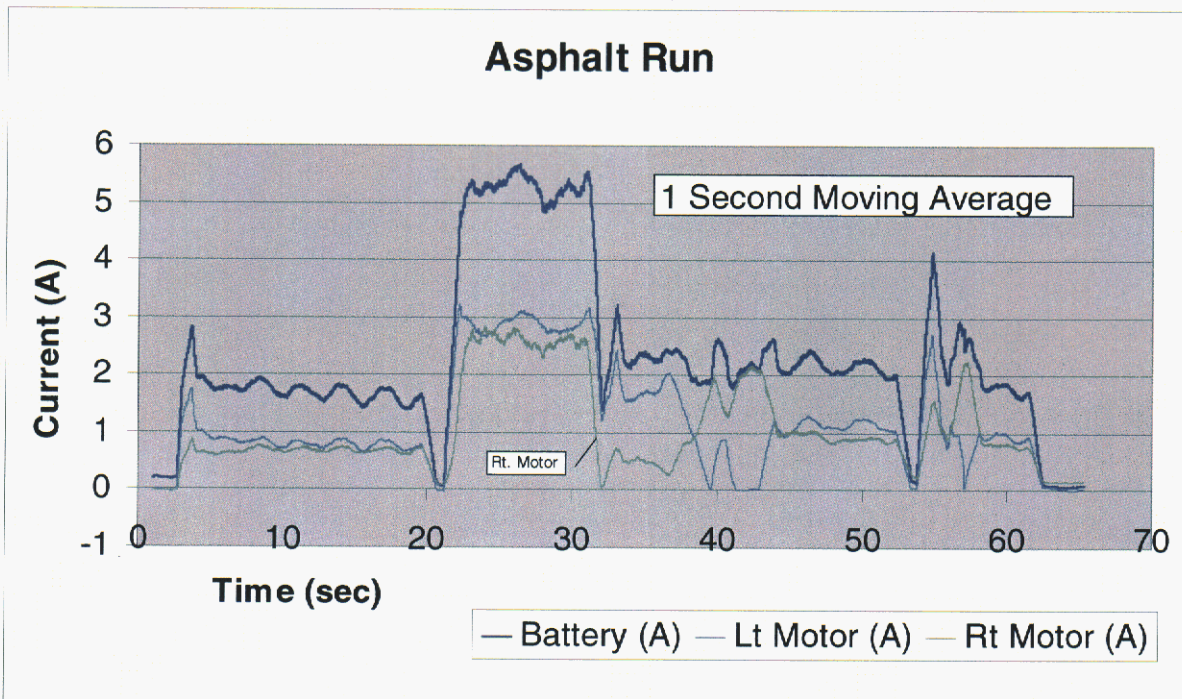


Figure 4c. Asphalt Surface: Forward, Spin-Turn, Reverse (1 sec average)

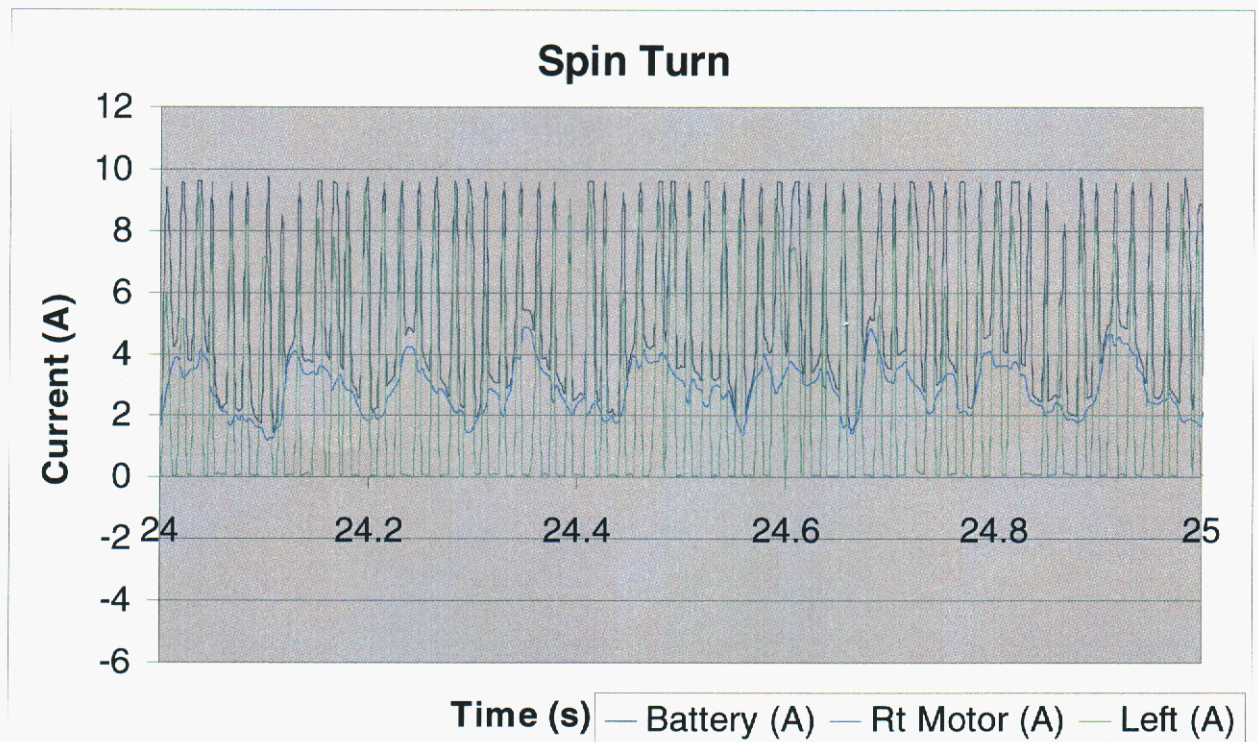


Figure 5. Expanded View of Spin Turn

The next run, shown in Figs. 6a., 6b. and 6c., provides data while the vehicle was climbing and then descending a packed dirt hill with a 15° slope. Current draw is much higher during ascent than descent.

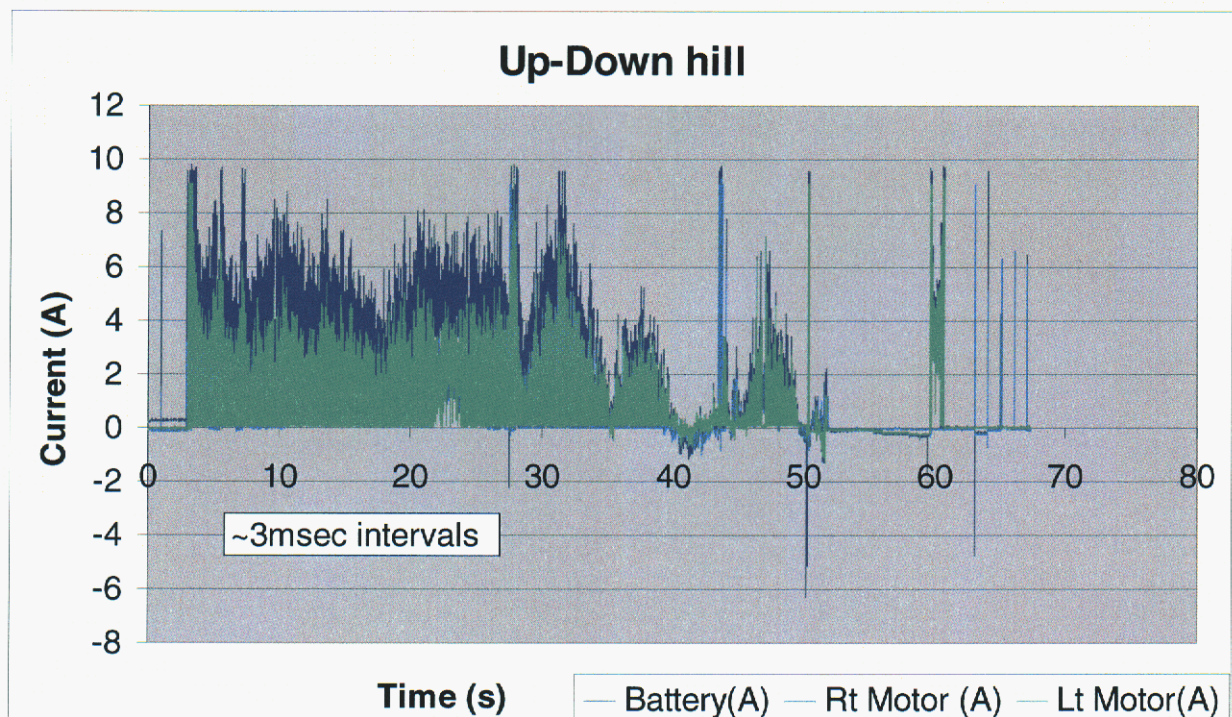


Figure 6a. Dirt Surface: Ascending and Descending a 15° Slope (~3msec intervals)

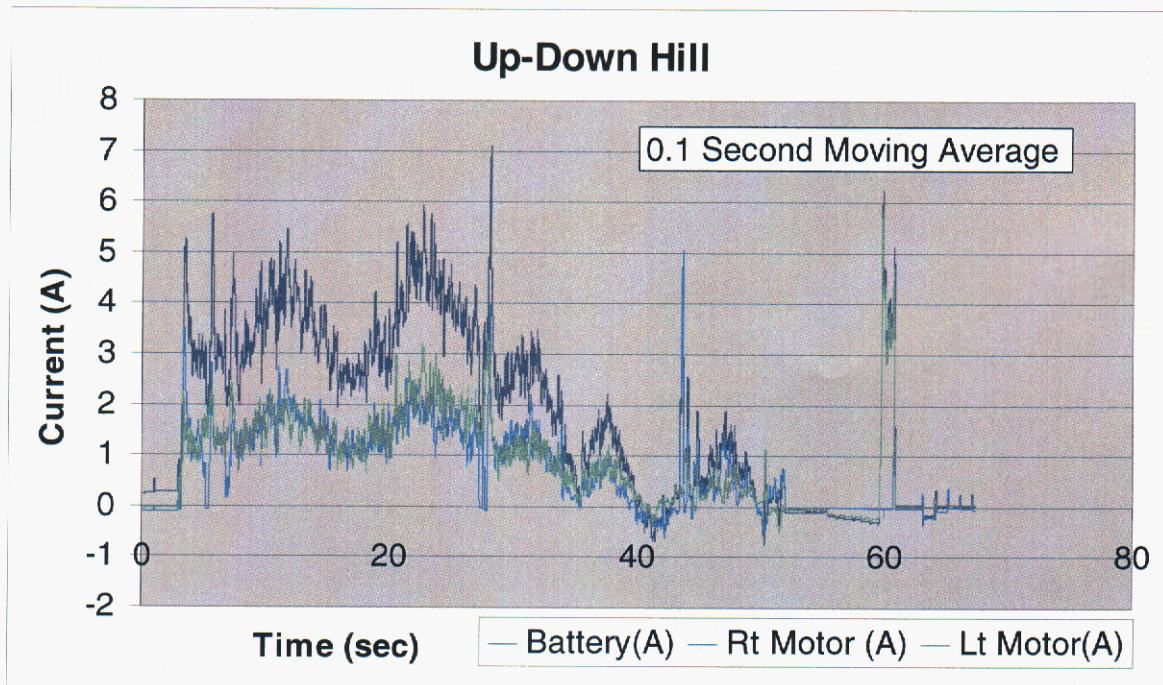


Figure 6b. Dirt Surface: Ascending and Descending a 15° Slope (0.1 sec avg.)

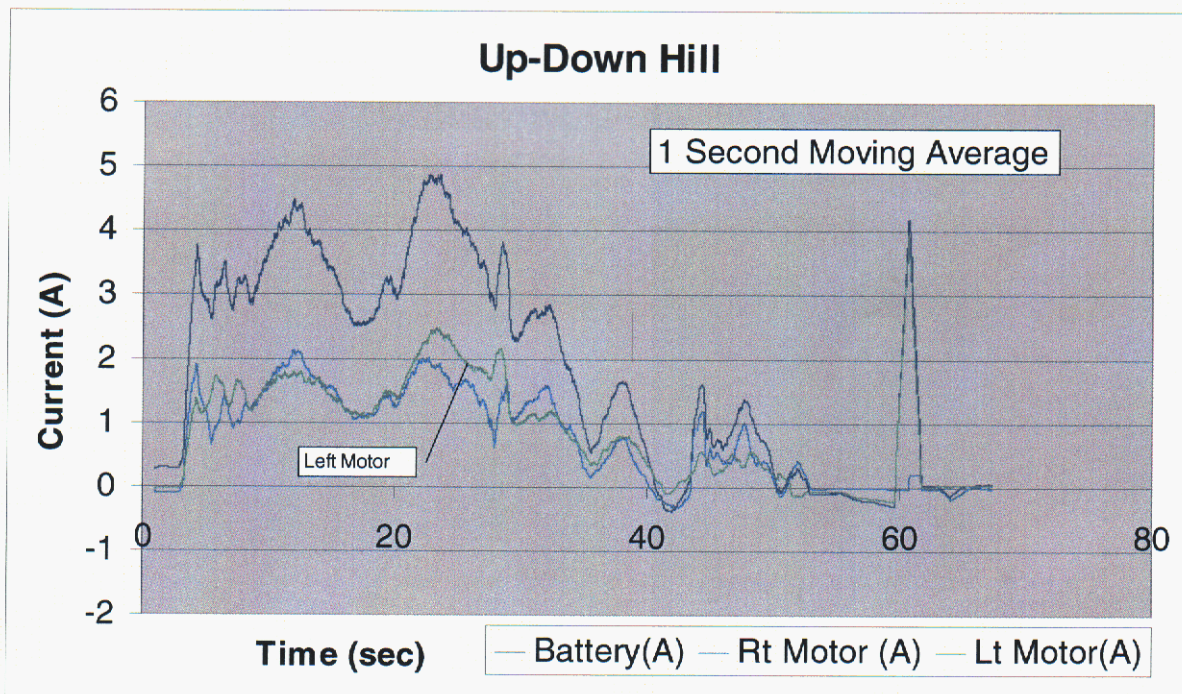


Figure 6c. Dirt Surface: Ascending and Descending a 15° Slope (1 sec avg.)

Figures 7a., 7b., and 7c. show data taken during a run on the dirt motocross track at the RVR. The vehicle started on level terrain and went downhill at about 15 seconds, after which it made a slow left turn and began climbing the next hill at about 75 seconds.

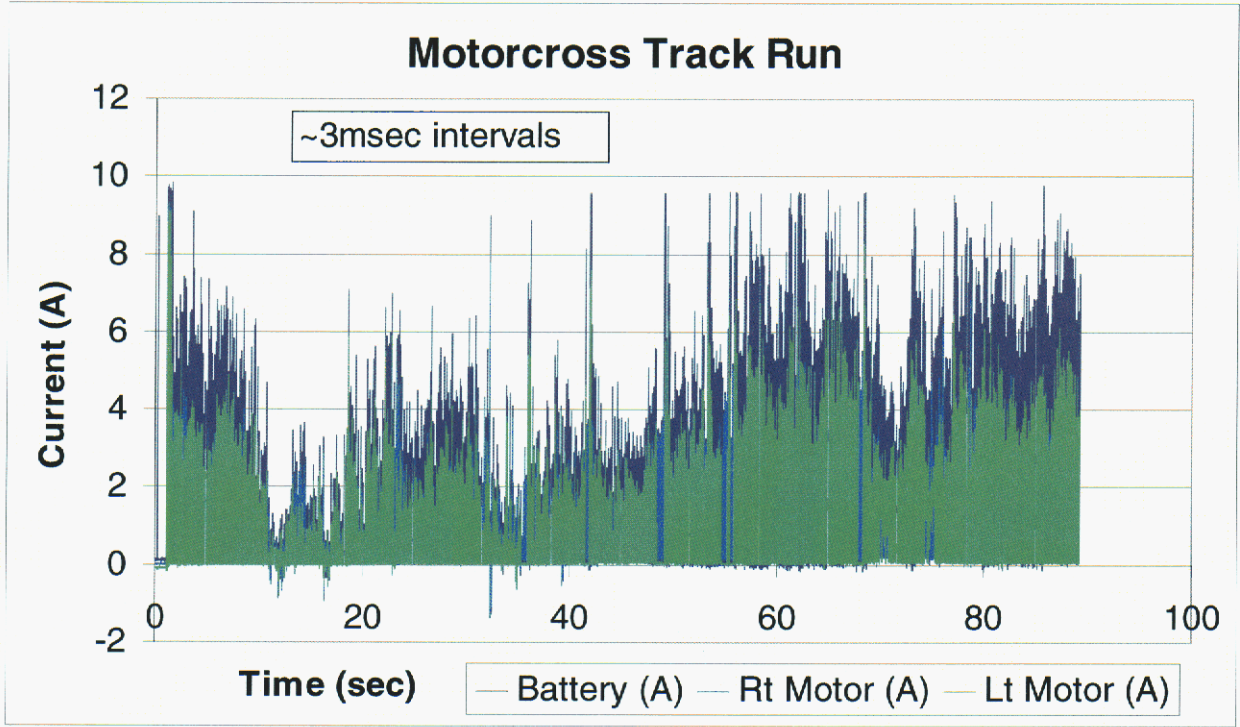


Figure 7a. Dirt Motocross Track: Descent, Turn, Ascent (~3msec intervals)

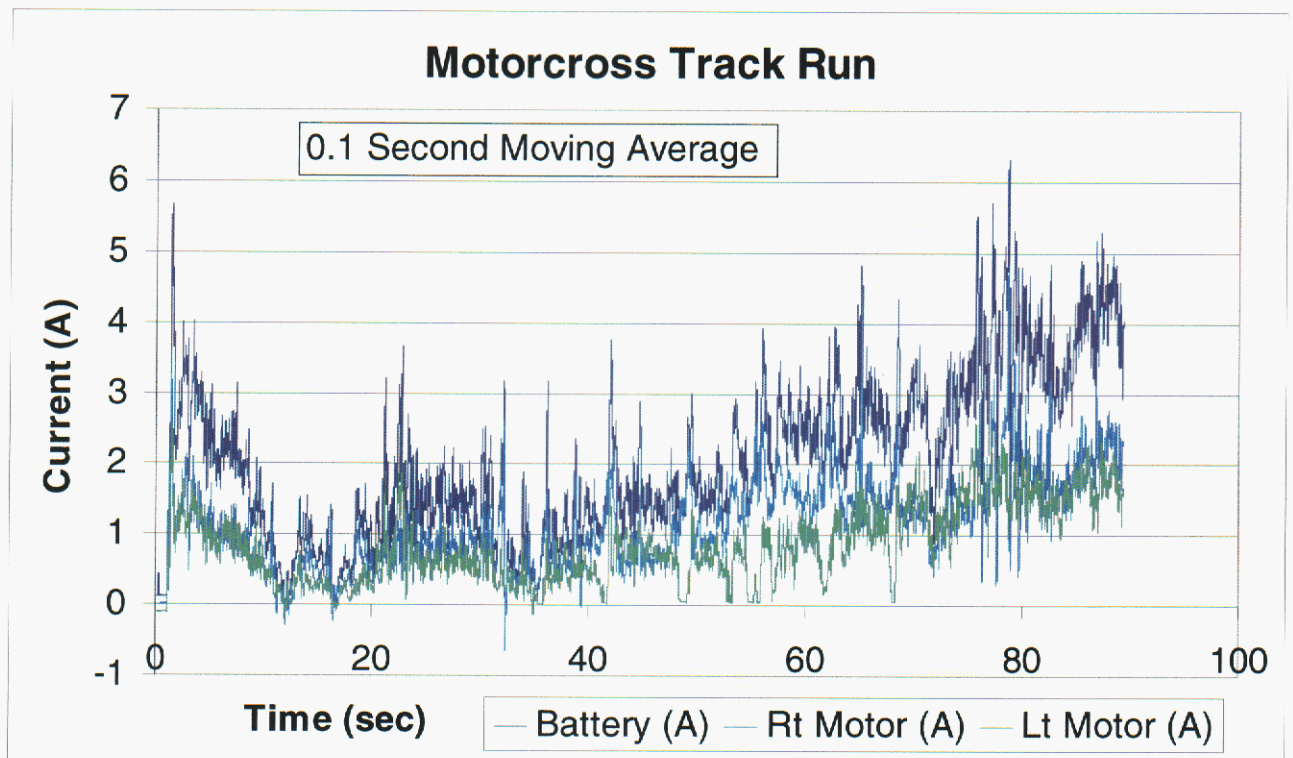


Figure 7b. Dirt Motocross Track: Descent, Turn, Ascent (0.1 Second Average)

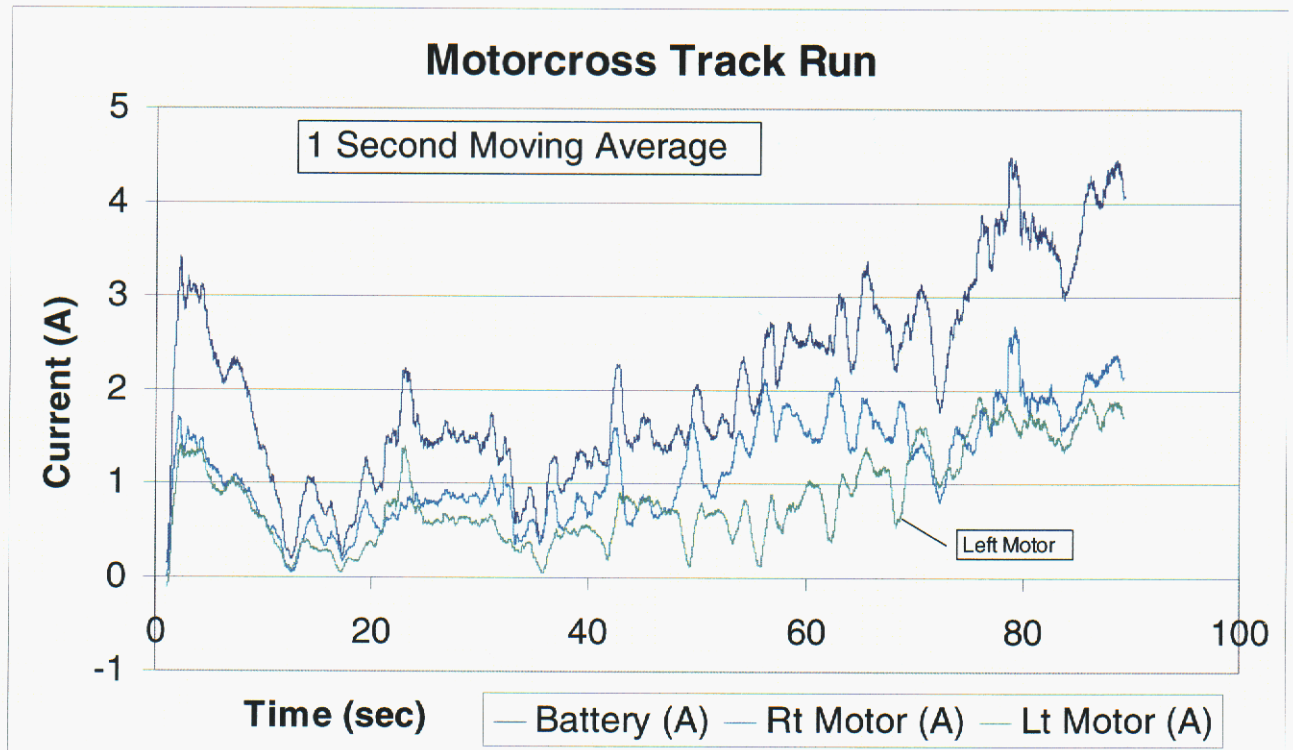


Figure 7c. Dirt Motocross Track: Descent, Turn, Ascent (1 Second Average)

Figure 8. shows a simple benchtop run of the vehicle with no load on the tracks. This data enables one to extract the parasitic load of the motors and flexing tread independent of the motive work being done. The first interval of data shows the vehicle in forward. The second interval is the vehicle in reverse. The third is a right spin-turn, and the fourth is a left spin-turn.

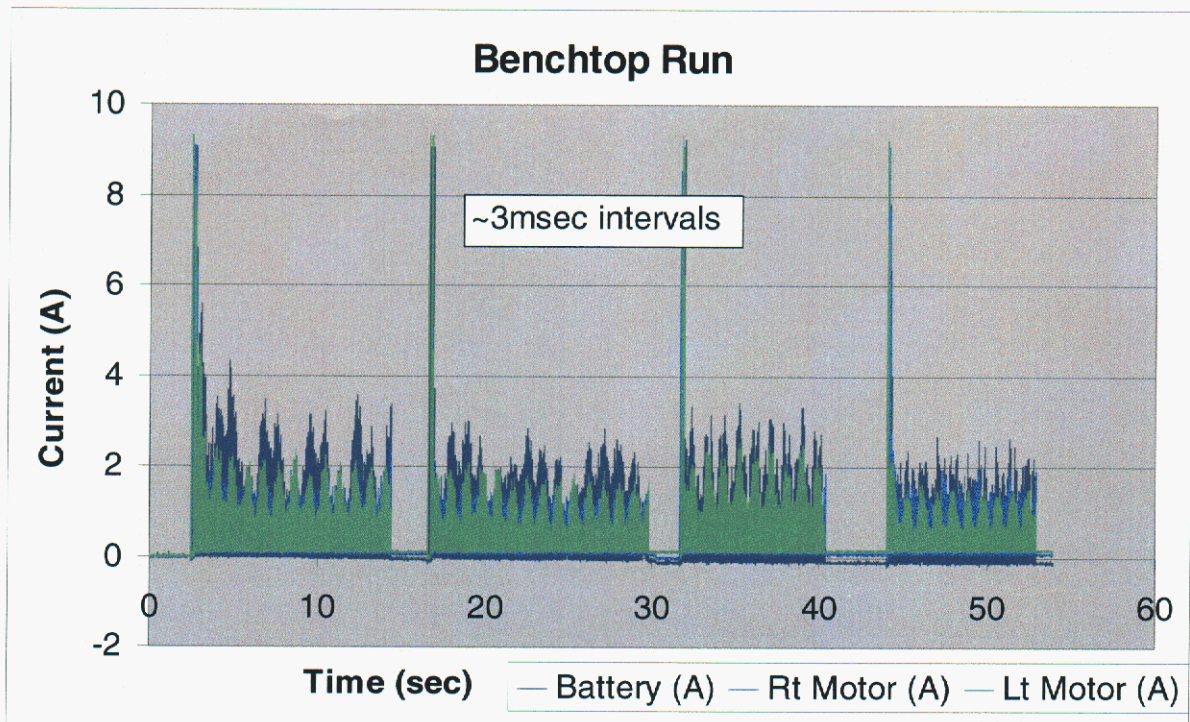


Figure 8a. Benchtop: Forward, Reverse, Left Turn, Right Turn

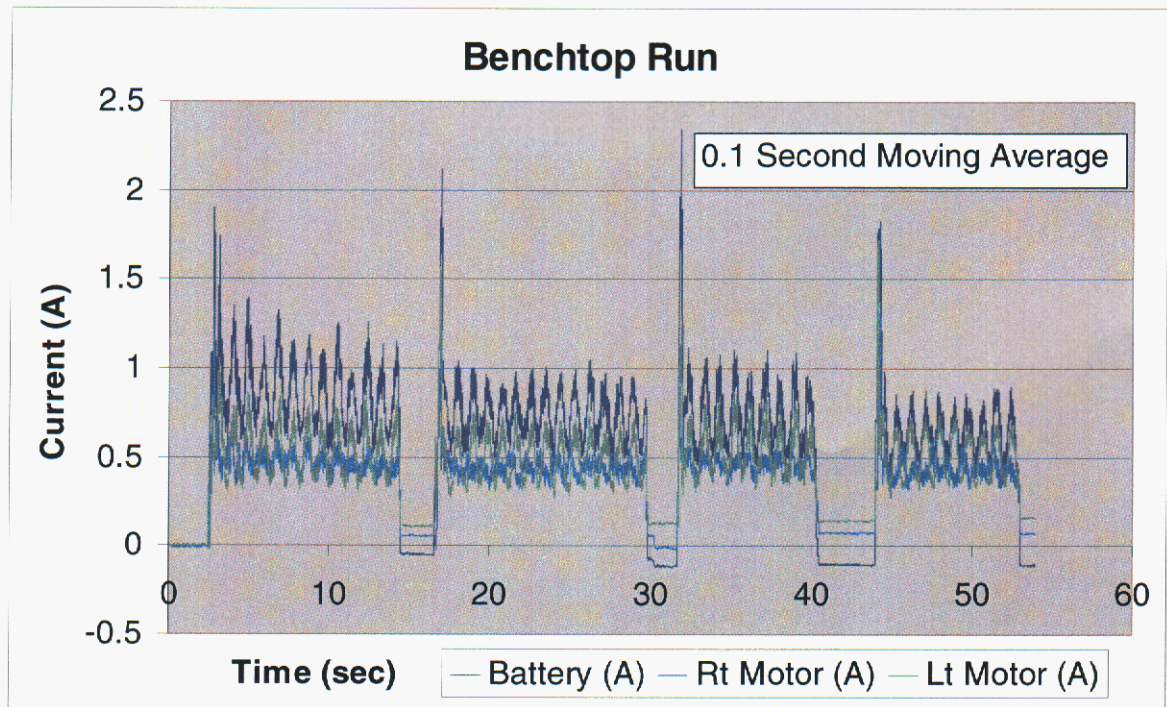


Figure 8b. Benchtop: Forward, Reverse, Left Turn, Right Turn (0.1 Sec. Avg.)

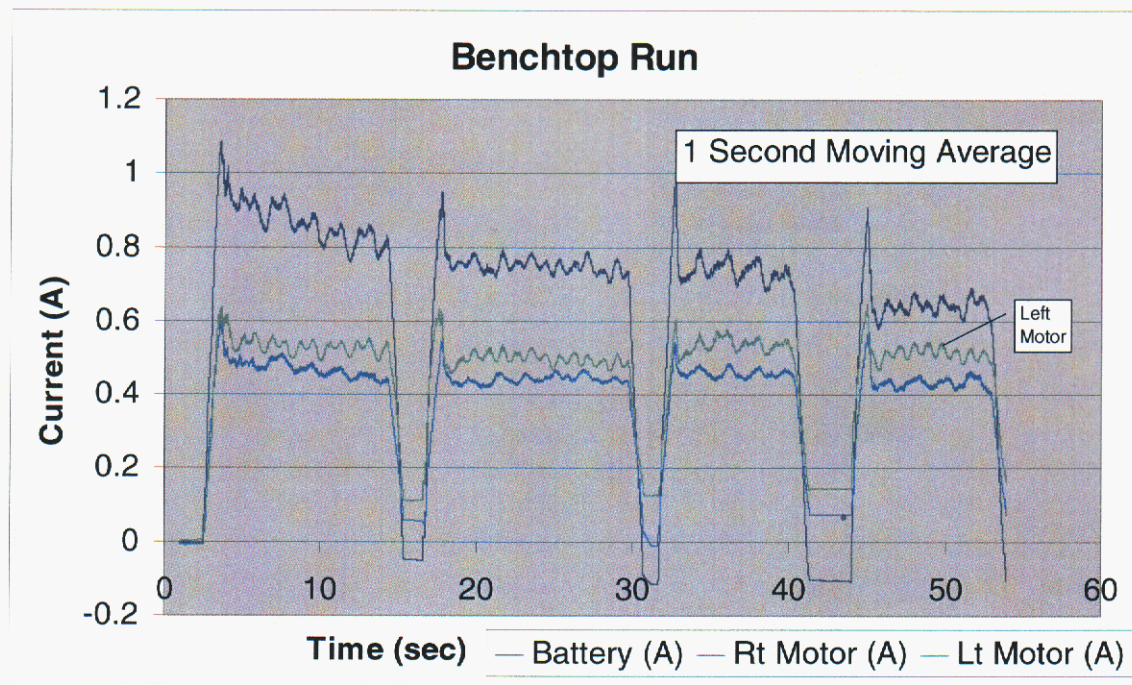


Figure 8c. Benchtop: Forward, Reverse, Left Turn, Right Turn (1 Sec. Avg.)

The results of these tests have been compiled into a table showing some duty cycle average and peak power requirements running under battery power. The vehicle battery system was nominally 24V, which was used to convert from amperes to watts. Peak values are shown for 0.1 second averages rather than the instantaneous values read every ~3msec. The high spikes observed in the 3msec readings are very short duration and have

little energy content. It is likely vehicle performance would be unchanged if the power system were unable to achieve these high values for these short durations.

Duty Cycle Element	Peak Power Requirement (W)			Avg Power Requirement (W)		
	Left Motor	Right Motor	Total	Left Motor	Right Motor	Total
Forward (Asphalt)	96	96	192	24	24	48
Reverse (Asphalt)	96	96	192	24	24	48
Spin Turn (Asphalt)	120	120	240	72	72	144
15° Ascent (Dirt)	72	72	144	48	48	96
15° Descent (Dirt)	24	24	48	12	12	24
Forward/Reverse Parasitics	36	36	72	12	12	24
Left Turn Parasitics	36	36	72	12	12	24
Right Turn Parasitics	36	36	72	12	12	24

Table 1. Duty Cycle Element Power Requirements

Fuel Cells

Although problems were encountered with the controllers of both fuel cells, we were able to gather basic data on the performance of the units. The underlying problem with the fuel cells was the controllers didn't operate properly. The controllers were supplied by H-Power along with the fuel cell stacks, but documentation and source code were unavailable. We were unable to get proper operation of the air pump, so we had to bypass the controller and power the air pumps directly from a 5V power supply. Additionally, the solenoids were bypassed by running a line straight from the regulators to the stack. We limited the stack temperature to 130° F to avoid potential damage. This, however, caused some difficulties in acquiring enough data to make accurate current-voltage curves. The problem was that the stack temperature reached 130° F fairly quickly (7 minutes), and had to be shut down until the stack returned to a safer operating temperature. During the shutdown period, no voltage was produced because the flow of hydrogen had to be cut off to reduce heat in the stack. Hydrogen would be allowed to re-enter the stack after it reached about 120° F, at which time the cell would give output voltage again and begin to heat up. It took only a few minutes to reach 130° F again, where it had to be shut down. Figure 9. shows the current-voltage curve and current-power curve for one fuel cell. Table 2. shows stack temperature rise rate for various power levels.

The current voltage curve we measured on these stacks was lower than the curve provided with the shorter 25-plate stacks used in tests two years ago. Those IV curves started at 30V at 0A, decreased to 25V at 2.5A, and dropped to 21V at 5A. Our present curve starts at 23V at 0A and drops to 15V at 2.5A. The power of the stacks previously went from 0W at 0A pretty linearly to 110W at 5.5A. We achieved a peak output of about 42W at 2.5A.

The capacity of the hydride beds indicates the theoretical energy storage content. The left fuel cell hydride bed took in a maximum of 1.9g of hydrogen after being run down to

empty, and the right stack 2.4g. This is significantly less than the 4 to 6g we recorded two years ago when testing these beds, so they seem to have lost some capacity.

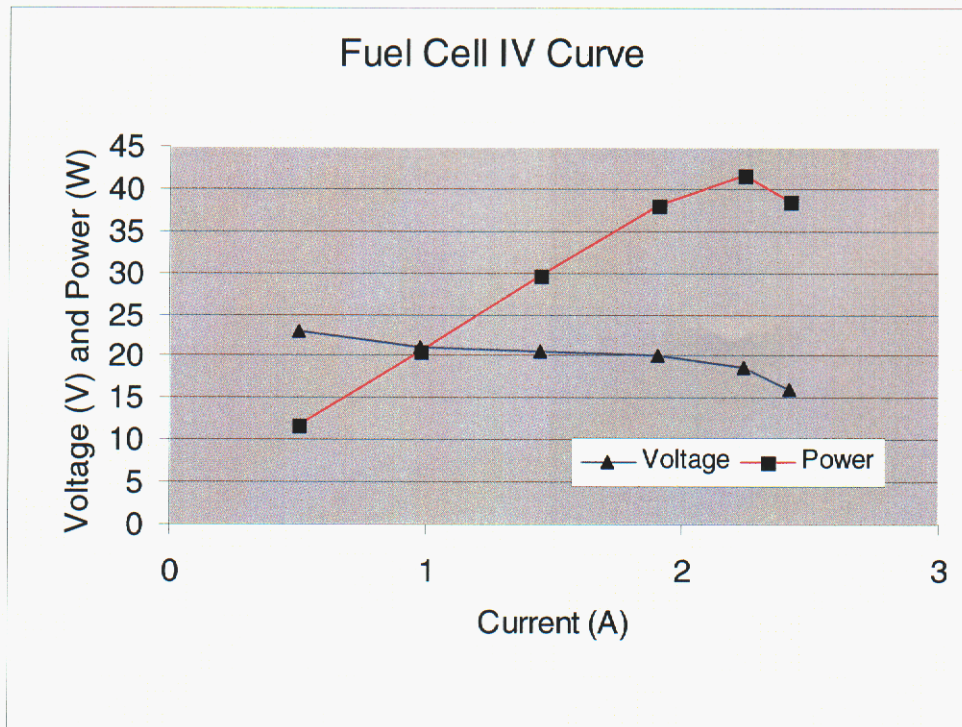


Figure 9. Left Fuel Cell Current-Voltage Curve

Power Level (W)	Temperature Rise (Deg F/min)
11	0.3
20	2.5
29	6
38	6.5
41	6.6

Table 2. Fuel Cell Stack Temperature Rise

Conclusions

Although the test program was not completed as desired, we were able to obtain some significant data concerning vehicle duty cycle power and energy measurements, as presented in Table 1. Additionally, we are able to draw some conclusions regarding the fuel cells. The stack that we tested and presented data on here peaked out at about 40W of power at which its temperature rise rate was around 6 degrees F per minute. The data taken on the vehicle showed that it requires about 1A per motor, or 24W at the 24V operating voltage of the batteries, to drive on asphalt, 2A per motor, or 48W, to climb a dirt hill, and 3A per motor, or 72W, to execute a spin turn. These are the average values. The instantaneous values with a battery are up to 9A (108W) for short duration pulses. The motors are driven using a pulse-width modulation (PWM), so it is probable that they can meet the short duration energy demand at currents less than 9A by broadening the

PWM duty cycle. However, we may find the fuel cell requires some form of energy storage device such as a supercapacitor or battery to provide additional energy for short duration events that require greater energy content.

The data indicates that the fuel cells as they are presently operating do not have sufficient power to perform a spin turn, and barely enough power to perform a moderate (15°) climb. Furthermore, the thermal rise rate of the fuel cells operating on the benchtop in open air with a fan-generated breeze is too high at power levels above 20W (about 1A) to permit sustained operation. Additional work is needed to optimize the cooling provided by blown air by designing effective ducting for use within the vehicle. It was suggested that the fuel cells may not be performing at their best due to drying of the membranes resulting from inactivity for many months. (This would have implications for fielded systems as well). If this is indeed the case, it may be reversible by continued operation allowing the membranes to gradually re-hydrate. Perhaps additional power can be extracted from the fuel cells if additional issues are identified and fixed.

While fuel cells offer significant benefits for extended mission profiles, these issues of matching available power to the dynamic vehicle requirements and the thermal rise rate of the stacks at higher power must be addressed before these units can safely be used to power the robot unit.

This work was performed as part of US Department of Energy contract DE-PS26-99FT14299 with the Fuel Cell Propulsion Institute entitled Advance Underground Vehicle Power and Control.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

Appendix A – Statement of Work for Sandia Test Program

SOW for
Sandia National Laboratories
Robotic Vehicle Range
Fuel Cell Vehicle Performance Characterization
6/20/01

Sandia will perform the following activities in support of the Fuelcell Propulsion Institute's program on fuel cells for underground vehicles.

Preliminary Duty Cycle Load Characterization

Use the robotic vehicle to characterize the load of elemental vehicle operations using a battery as a power source.

- 1) Check the proper operation of the RATLER™ vehicle while using batteries for power. Do what is necessary to get vehicle operational.
- 2) 10/31/01 Adapt data logger system to monitor temperature and battery voltage and currents. We plan to use our A-Engine86 platform and small Hall-effect current sensors. Work is needed on logger software, sensor interface hardware, and calibration of the sensors. A fallback position is to use the dataTaker platform (which only logs at 1Hz).
- 3) Identify elemental vehicle operations and develop a detailed test plan to characterize the load of these operations. Characterization will include tractive effort that measures force the vehicle can apply on a variety of surfaces against a vertical wall.
- 4) Perform measurements and reduce the data.
- 5) 12/31/01 Prepare write-up of test results.

Bench-top Evaluation of Fuel Cell Performance

Evaluate the current, voltage, and temperature rise rate of the fuel cell stack vs. load. Thermal performance is a key issue we will be investigating and will depend on stack mounting configuration and cooling design. We will start with the stack operating in free air and gradually work towards the stack operating within the confines of the vehicle operating on the bench-top. We will also start by characterizing performance with a resistive load bank (steady load) and then characterize performance with the vehicle motor load (variable or spiky load).

- 1) Set up fuel cell on bench and check out refueling procedure.
- 2) Fabricate variable load resistive load bank (0 to 100W).
- 3) Set up measurement equipment including current, voltage, and thermal sensors and associated equipment. Confirm thermal monitoring approach and setpoints with H-Power.
- 4) Test each fuel cell and hydride bed to ensure proper operation. Identify capacity of each fuel cell by weighing before and after refueling. Compare to total current produced. (Current is proportional to hydrogen usage.) Compute system efficiency. Investigate use of flow meter to measure hydrogen use real-time on the bench-top.
- 5) Test each fuel cell over its full power range in free air using the static load bank to characterize current, voltage, and temperature and/or temperature rise rate. Check

control shutdown for over-temperature conditions. Compute system efficiency at various load levels.

- 6) Repeat tests with various levels of shrouding and enclosure building up to that of a vehicle. Install fuel cell in a vehicle on the bench for final level of testing.
- 7) Fabricate a method to provide a steady load to the vehicle's wheels on the bench-top test.
- 8) Perform tests over full load range in vehicle using vehicle drive train and wheel load. If shutdown occurs as before, work with H-Power to determine if the control setpoints are the cause. Develop filter on voltage input to controller or work with H-Power to modify the controls as necessary.
- 9) Repeat tests adding load spikes (possibly manually) to vehicle's wheels to simulate road roughness.
- 10) 2/28/02 Prepare write-up of test results and of refueling time.

Outdoor Tests of Vehicle with Fuel Cell Power System.

- 1) Repeat outdoor elemental operation characterization tests using vehicle with fuel cell power system.
- 2) 3/30/02 Prepare write-up of test results.

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